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Influence of different curing methods on the compressive strength of ultra-high-performance concrete: A comprehensive review

Hussein Hamada [a,*], Alyaa Alattar [b], Bassam Tayeh [c], Fadzil Yahaya [a], Ibrahim Almeshal [d]

[a] Faculty of Civil Engineering, University Malaysia, Pahang, Malaysia
[b] Northern technical university, Mosul, Iraq
[c] Civil Engineering Department, Faculty of Engineering, Islamic University of Gaza, P.O. Box 108, Gaza Strip, Palestine
[d] School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, Pulau Pinang, Malaysia

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ABSTRACT

Ultra-high-performance concrete (UHPC) is a distinguishing material used in new construction and conjunction with conventional concrete. However, some issues limit the wider application of UHPC, such as high autogenous shrinkage, low workability for large-volume production, high cost, and unpredictable peak curing method. This comprehensive study aims to clarify the different effects of curing methods on the strength development of normal concrete and UHPC. The present article reviews studies that used microwave curing, autoclave curing, carbon curing, steam curing, electric curing, ambient and air curing and water to determine their effect on compressive strength. All the curing methods achieved satisfactory values of compressive strength. However, it is not practical to specify the peak curing regimes for concrete or UHPC since the best results need critical monitoring of curing parameters. The time when the samples are demolded and subjected to hydrothermal and thermal treatments varies in the literature since it depends on the binder setting time. That time should be carefully selected to avoid adverse effects and to maximise output. A combination of these curing regimes could be used together or with pressure or heat to further improve the compressive strength. In addition to the type of materials used, the curing temperature and duration significantly affect the overall performance of concrete. This review is expected to guide future research and provide an overview of the research field.

1. Introduction

Ultra-high-performance concrete (UHPC) is a new class of concrete developed in France in the 1990s with superior characteristics, including high workability, high compressive strength, increased ductility, and high resistance to environmental attacks [1–3]. UHPC is generally defined as concrete with a compressive strength greater than 150 MPa. UHPC is typically made with high-strength steel fibres, fine sand, cement, fly ash, a large volume of silica fume, and a low amount of water (w/c ratio less than 0.20) [4–7]. Due to its excellent strength, it has been successfully applied to long-span bridge structures, the wet joint connection of prefabricated building components, reinforcement, and repair of some major projects [8–10]. In the early stage of casting UHPC, the autogenous shrinkage is

* Corresponding author.
E-mail address: enghu76@gmail.com (H. Hamada).

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an essential inducement of cracking [11,12]. The internal humidity of the UHPC matrix gradually decreases and the capillary tension of the pores increases due to continuous hydration, which leads to the concentration of stresses and the formation of internal and external cracks [13,14]. The autogenous shrinkage value measured can reach 440 micro-strains at the age of 36 h, with further slowly increasing after the final setting [15,16]. As a result, it becomes imperative to cure the UHPC matrix to mitigate the drop in its internal relative humidity, which is a significant concern [5,17–19].

The curing of concrete is a consequence of chemical reactions that occur during cement hydration and is called a set of concrete [20,21]. Environmental conditions might affect the properties of concrete during setting, either chemical reactions or hydration during the hardened state. In general, the limitations that should be considered during concrete setting are high temperature, low humidity, wind and other factors [22–25]. A strong wind, high temperature and a dry environment can affect mainly the acceleration of two phenomena that affect concrete curing, namely, water evaporation due to cement hydration and speed of cement hydration [26,27].

The casting of concrete at high temperatures is not recommended especially when the temperature reaches 35 °C [28–30]. Many standards can be adopted to afford the arrangements of temperature–wind values that frontier the situation for laying concrete [31, 32]. Low temperatures are also not recommended during concrete casting [33,34]. The temperature should be not less than 5 °C because the chemical reactions of cement hydration cannot occur at such temperatures. Additionally, low temperatures up to 0 °C might cause concrete damage due to the expansive process of water freezing, resulting in cracks on the concrete surfaces [35,36].

In the process of UHPC production, it is recognised that curing process plays a major role to guarantee its outstanding performances [37–39]. Curing phase has a vital role on strength development of UHPC. There is no standard curing condition for UHPC as of now. Generally, UHPC is cured in two types of curing regimes (i) autoclave curing and (ii) thermal curing. The thermal/heat curing includes steam curing, hot water bath curing and hot air curing. Autoclave curing is done by applying heat and pressure simultaneously on fresh samples [40–43]. Heat treatments have generally been applied to make UHPC to accelerate the hydration process and increase the density, leading to ultra-high compressive strengths. In the case of precast UHPC products, heat curing at 90 °C for 48 h can be easily applied; thus, the target compressive strength (≥180 MPa) is generally achieved. However, in some special cases (e.g., the joints of precast segments [44] and the rehabilitation of existing structures [45]), UHPC is typically cast-in-place; thus, the use of heat treatments is limited due to the difficulties in controlling the temperature and moisture at a construction site [37,46,47].

Compressive strength is a critical factor in the design and construction stages. Increasing the compressive strength can improve concrete manufacture by decreasing the production period, energy consumption and labour force, thereby ensuring eco-friendliness [48,49]. The development of early-strength concrete is affected by numerous factors, such as cement type, curing conditions, water cement ratio, aggregate size, mineral and chemical admixtures, quality and gradation. Numerous approaches can be used to increase the early strength of concrete. Appropriate temperature and moisture conditions are required to guarantee the degree of strength and hydration development of concrete during the curing period.

2. Scope and methodology

This review article aims to present the effect of various curing regimes on the strength of normal concrete and UHPC. The collected papers are integrated according to subsequent factors. The results of the compressive strength of UHPC samples were characterised as percentage change compared with control UHPC samples. Seven curing conditions were adopted, namely, microwave curing, autoclave curing, carbon curing, steam curing, electric curing, ambient and air curing and water curing.

3. Curing regime

The main purpose of curing is to obtain concrete with high strength and durability through complete cement hydration, which leads to denser microstructure by applying various heat treatments during concrete curing [40,50–53]. Therefore, curing can reduce cracks produced by shrinkage [54] and improve concrete strength. Furthermore, normal curing is inadequate for concrete [55] because the hardening process of RPC will be very slow and the compressive strength acquired is insufficient [40]. Therefore, RPC samples should be cured by unconventional regimes, such as hot, steam or autoclave curing. The hot dry air is the most suitable temperature for RPC curing, which might reach up to 250 °C; however, exposure of the samples to temperatures higher than 250 °C can reduce the compressive strength rate, causing dangerous deteriorations in the microstructure owing to the presence of cracks and pores on the sample surface [53,56–59].

The highest benefits of high-temperature curing can be identified as follows:

(1) Producing a new crystallised hydrate C-S-H to form a dense microstructure and a high-performance concrete due to surge insertion of matrix adhesion [52]. The compressive and flexural strengths of concrete samples increased by 16 and 0.7 MPa with an increasing temperature rate of 10 °C [52].
(2) The heat treatment assists in forming secondary hydrates for quartz powder due to the pozzolanic reaction [40,60].
(3) Heat treatment adjusts the chemical configuration of hydrated particles in RPC, thereby decreasing the CaO/SiO_2 and the H_2O/CaO ratio. All these responses result in the production of C-S-H [40,61].
(4) Autoclave curing is conducted by applying a mixture of pressure curing and heat curing to RPC. Higher values of compressive strength and flexural strength (20–30 %) are obtained in autoclaving compared with those in normal water curing. Autoclave curing reduces the porosity and increases the density, thereby enhancing the high performance of concrete. Nevertheless, temperature and pressure beyond the critical time have a destructive influence on the microstructure and mechanical performance of concrete samples [52,62–64]. The benefits of autoclave curing can be identified in some points:

a) The compressive strength produced might reach up to 500 MPa when pressure is between 50 and 100 MPa) [59,62,65–68].
b) Increasing the temperature rate by 10 °C leads to an increase in flexural and compressive strength by 0.5 and 4 MPa, respectively [52].
c) Autoclave curing increases the adherence between fibre paste of RPC, possibly enhancing the compressive strength and reducing paste voids, hereafter improving the microstructure of concrete [62,69].
d) Autoclave curing reduces the unit weight and increases the modulus of elasticity of concrete [62].

3.1. Microwave curing

Microwave heating is a significant method used to treat concrete samples owing to its low energy consumption and high efficiency. Microwave curing can revolutionise concrete curing [70]. Microwave heating can increase the early strength of concrete during short curing time compared with traditional steam curing [71]. Recycling concrete aggregate is another application of microwave heating, where a particular portion or a component from concrete is taken out [72–74]. In addition, microwave heating provides a selective heating property to produce a recycled aggregate that can be used in other concrete production methods [75–79]. Shao et al. [70] conducted a comprehensive review of studies that address the curing of concrete by microwave heating, which has low energy consumption and high efficiency. Microwave curing has a significant role in accelerating concrete curing. Leung and Pheeraphan [80] determined the potential of this method to achieve early high-strength pre-casted concrete. Many factors, such as duration and application of microwave, microwave power and others, affect concrete development. The early compressive strength values of 29.5 and 35.4 MPa were produced with two different w/c, namely, 0.40 and 0.325, respectively, and 270 min.

Prommas and Rungsakthaweekul [81] used microwave curing to improve the compressive strength of concrete. They inserted concrete samples with a size of 100 mm × 100 mm × 100 mm after casting and then removing them from moulds. A commercial kitchen microwave oven with inside cavity dimensions of 268 mm (height) × 390 mm (width) × 400 mm (depth) was adopted to achieve microwave curing. The compressive strength increased steadily to 30.82, 48.2 and 58.25 MPa for 3, 7 and 28 days, respectively.

Moisture has a significant effect on the heating method to be a good- microwave ↱absorbing material. Studies have reported that increasing the ↱water content of concrete led to the weakening of the microwave process ↱[82–85]. New concrete curing can be achieved at specific temperatures, time and humidity conditions [70]. Compressive strength is a critical factor in the prophase structural design period and the construction period.

Microwave has been studied for quickening curing form for the repair of cement mortar and freshly cast concrete. Microwave heating was adopted by researchers to increase the early strength for newly poured concrete [86]. Recent investigations on mortar repairing showed that in a short heating ↱time, the microwave heating of concrete could accelerate the hydration of old ↱concrete, enhancing the overall efficiency and guaranteeing its upcoming ↱utilisation.↱ Table 1 shows the studies that adopted microwave curing

Table 1
Previous studies that adopted microwave curing.

Ref.	Heating power exposed	Heating duration (min)	Effect of microwave curing
[80]	0.4 and 0.325	45 and 90	Obtain very high compressive strength at early curing age.
[87]	400, 800 W	10, 15 min	Development of compressive strength at an early age for concrete specimens subjected to the microwave is higher than that of concrete specimens achieved by water or air curing.
[88]	900 W	5 min	Microwave curing techniques can enhance the early strength due to accelerating the cement hydration process better than that corresponding to water curing.
[89]	240, 360, 600 W	0–120 min	Microwave curing for two hours led to higher compressive strength than those of mortar samples curried by heating at 75 °C for 2-days. Microwave curing results in uniform and dense microstructure.
[90]	300, 350, 400 W	45 min	Microwave curing of concrete specimens achieved high performance in both early and later curing compared to that of concrete comprising different accelerators curing
[91]	150–1250 W	15–120 min	Microwave curing has an important impact in enhancing the early strength of compressive and flexural strengths higher than that of strength obtained at a later age.
[92]	140,260, 440 W	30, 60, 120 min	Microwave curing enhances the compressive strength of mortar at an early age, up to 28 days, somewhat improving the mortar's porosity, whereas it considerably decreases the pores volume that has particle sizes more than100 nm.
[93]	260 W	35, 45, 55 min	Microwave curing enhances the process of cement hydration and somewhat increases the porosity. The small particle size somewhat influenced decreasing the compressive strength of cement mortar.
[94]	10 GHz	0–60 min	The cement type and w/c ratio are the main factors that affect the relative permittivity and conductivity of cement, which leads to changes in the hydration process
[95]	900 W	3, 6, 9, 12 min	Microwave curing was active at an early age, up to 7 days, leading to a higher microstructure porosity. That leads to an increase in the compressive strength, more than that of the water curing.
[96]	600 W	30 min	Microwave curing has a vital role in acceleration of the chemical reactions with different volumes of steel fibre; this effect on carbonation and hydration increases steadily.
[17]	700 W	60–240 s	The microwave curing method contributed in increasing density of UHPC samples and improved the overall performance of concrete samples treated by microwave.
[97]	800 W	60–240 s	Microwave curing led to a quick increase in the early compressive strength of UHPC. The compressive strength of C30 concrete developed to 10.3 MPa for 12 h only.

as a new technique.

Li et al., [96] used microwave curing for treatment of UHPC reinforced by steel fibres. The concrete samples were heated at 80 °C for 30 min. The compressive strength and other concrete properties were determined. The existence of steel fibre contributed mainly to increase the compressive strength of UHPC treated by microwave curing compared with that of other curing methods (Fig. 1).

Zhang et al. [17] showed the effect of microwave pre-curing on the properties of UHPC, including compressive strength. The concrete specimens were exposed to microwave pre-curing for 60–240 s. Microwave curing can increase the compressive strength, as illustrated in Fig. 2.

3.2. Autoclave curing

Autoclave curing is a novel method carried out by special equipment to provide high temperature and pressure. This method has been adopted to achieve concrete with high compressive strength and performance [98–102]. Tian et al. [98] reported that the high early strength of concrete within 3 h increased dramatically due to the use of different curing regimes, such as autoclave (AC) curing (Fig. 3).

The compressive strength improved to 59 MPa instead of 34 MPa due to increasing curing temperature in the autoclave from 150 °C to 175 °C. Nevertheless, an additional upsurge in prolonged or temperature curing time did not increase the compressive strength. Comparable results on compressive strength were acquired by Manso et al. [103]. The developed strength of concrete mixtures with a replacement level of 43% of cement was similar to that of the cement-based control mixture. Table 2 shows the effect of autoclave curing on the compressive strength of concrete in previous studies.

Autoclave curing has led to a compressive strength of more than 500 MPa due to heat treatment at 250 °C and pre-set pressure of 60 MPa [68]. Bonneau et al. [108] studied the performance of RPC in a steel tube; the compressive strength was 285 MPa at 90 °C and under low-pressure steam curing. Teichman and Schmidt [109] investigated the durability and strength properties of RPC. The RPC specimens were arranged with pre-set pressure of 50 MPa. The compressive strength reached 487 MPa. Topcu and Karakurt [110] examined the influence of steam curing, hot water bath and autoclave curing on the improvement of compressive strength of RPC. The compressive strength achieved was 253.2 MPa.

Shaheen [111] adopted autoclave curing to produce RPC with a load of 50 kN for 24 h and a temperature of 150 °C. The compressive strength produced was between 243 and 288 MPa. Other study used mineral admixtures with RPC under various curing conditions [112]. Autoclave curing was conducted at 2 MPa and 210 °C for 8 h. The highest compressive strength of 273 MPa was produced using autoclave curing, and this value was higher than that produced by other curing conditions. Aydin et al. [113] examined the influence of three curing methods on various mixtures and compared them with normal curing. The methods adopted were atmospheric autoclave curing, steam curing and a mixture of autoclave and pressure curing. Steam curing improved the 7-day compressive strength by 11–36 % compared with that of 28-day compressive strength in the case of water curing. Autoclave curing within only 8 h presented superior compressive strength performance than steam curing for 7 days (Fig. 4).

Wongkeo and Chaipanich [114] investigated the compressive strength of high-strength lightweight concrete (LWC) made of silica fume and coal bottom ash under air and autoclave curing conditions. The LWC autoclaved for 360 min achieved similar compressive strength to the LWC containing bottom ash after treatment by air curing for 28 days.

3.3. Carbonation curing

Cement concrete samples treated at early curing age with high CO_2 and carbonation curing displayed better quality, namely, improved durability and mechanical properties [115–118]. Carbonation curing displays more benefits than conventional curing in precast concretes because it consumes lower energy than steam curing, which needs preservation of relative humidity and high temperatures [119,120]; it is also less time consuming than water curing because it allows recently concrete samples to strengthen

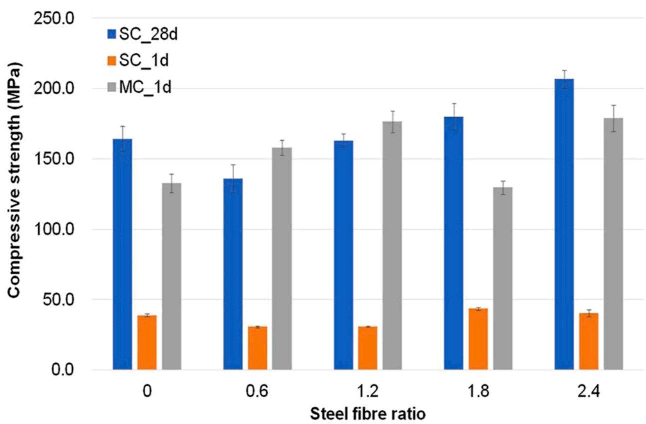

Fig. 1. Compressive and flexural strength of all UHPC specimens [96].

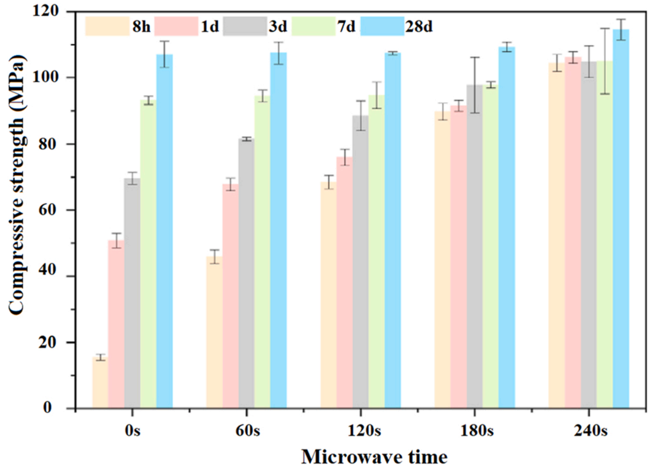

Fig. 2. Compressive strength values after microwave pre-curing [17].

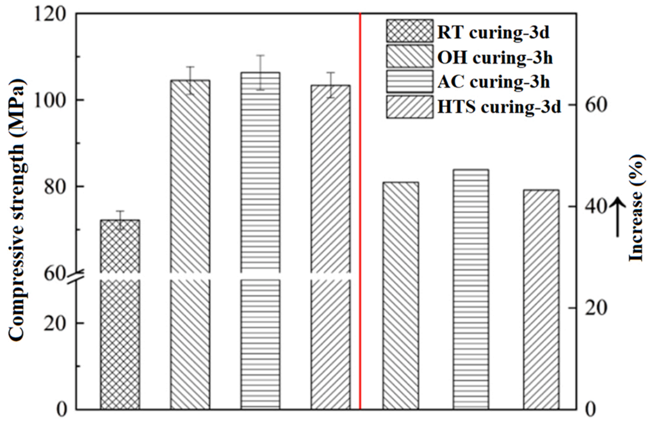

Fig. 3. Compressive strength values obtained by autoclave curing [98].

Table 2
Effect of autoclave curing on concrete strength.

Ref.	w/c	Heating rate and time	Materials used	Effect on compressive strength
[98]	0.24	90 min	Cement with silica fume and fine silica sand	Autoclave curing has a high compressive strength up to 105 MPa for 90 min.
[104]	0.3	operating temperature from 50 °C to 1000 °C with a heating rate of 10 °C min1	Cement, Dune sand, and white sand	Autoclave curing improved the compressive strength of concrete made of dune and white sands
[105]	0.5	900 °C at a heating rate of 20 C/min	oil-based drilling cuttings pyrolysis residues (ODPR) and fly ash	The compressive strength of concrete autoclave cured fundamentally fulfil the Chinese standard requirements.
[59]	0.23	6 h, 8 h, 10 h and 12 h	silica fume and different dosage of fly ash	Autoclave curing successfully increases the compressive strength of UHPC containing fly ash increased by 37.5%
[106]	0.5, 0.6, and 0.7	The microwave heating temperature was 50 °C,	carbide slag to quicklime	microwave pre-curing technique has positive influence on compressive strength of concrete
[107]	0.26	10 °C/min	Nano-SiO_2 and cement	The microwave of concrete containing Nano silica has improved the performance of concrete

more quickly. Furthermore, some industrial wastes or minerals might be steadied in cement concrete by carbonation curing, leading to minimal utilisation of cement and reduced emissions of CO_2 due to cement production [121,122]. Consequently, carbonation curing can be considered a promising method in cement concrete production because of its benefits: ↱(1) high possibility of storage and utilisation of CO_2 in curing of cement concrete samples, (2) improved mechanical and durability of cement concrete samples and (3) enhanced properties of precast concrete, thereby achieving many benefits in terms of economic aspect. This paper aims to explain the

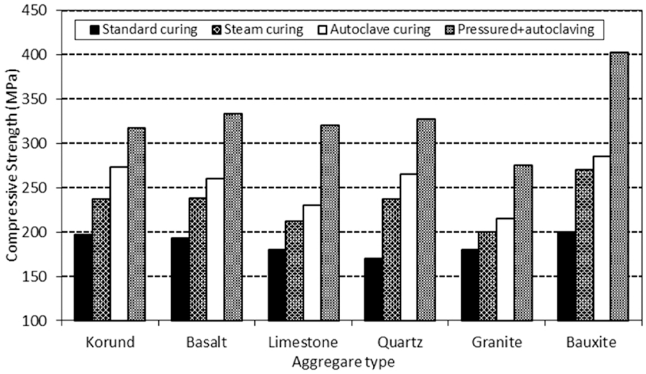

Fig. 4. Effect of different curing methods on the development of compressive strength [113].

important considerations and new developments on carbonation curing in the cement concrete industry.

Carbon curing is based on the carbonation reaction between CO_2 and cement paste. Carbon curing assists in the carbonation of whole concrete mixtures after concrete production. Carbonate is a new technique for cement mix, and it can improve concrete quality and accelerate curing time. Carbon curing is affected by some factors, such as temperature, CO_2 purity, humidity, ↱carbonation pressure, carbonation period and sizes of the produced concrete samples. ↱Carbon curing produces high strength throughout the condensation of novel aggregates and cement pastes [123–126]. The total technique after concrete moulding is similar to carbon conditioning. Fig. 5 shows the device utilised in typical carbon curing.↱

Li, Xiao [128] and Wu, Zhang [129] individually reported the carbonation process for 21 days. Carbonation curing for materials extremely decreases the surface area of a cylinder. The required time for the cement to be completely ↱carbonated was increased due to the reduction of surface area required for easy carbonation. Table 3 shows the effect of carbon curing on concrete strength. The reaction between carbon oxide (CO_2) and calcium hydroxide (CaOH) during carbonation curing will decrease the pH of the cement paste [120]. The corrosion issue is more probable to occur once the whole concrete sample has been subjected to carbonation because the direct contact of the cement to the reinforcement bars directly leads to carbonation [127]. Table 3 shows the effect of the duration and pressure of carbonation with other factors on the compressive strength of concrete.

Treatment of concrete samples by CO_2 curing is recommended to improve the concrete properties as well as steel corrosion and chloride ingress in recycled aggregate concrete [141,142]. The curing condition and duration affect chloride ingress into concrete samples. The resistance to chloride entry enhances with increasing curing duration, and the development of the resistance at an early age is more clear [143,144]; this is due to the reactions of hydration that improves due to increasing curing duration, resulting in a denser microstructure and lower chloride entrance into recycled aggregate concrete [142]. Carbon curing enhances new cement binders [124,145,146]. Carbon curing shows a definition comparable with that of the addition of mineral admixtures as an improvement [145,147,148]. Silica gel and $CaCO_3$ in the pore structure are products of carbonation and can increase the solid volume [117,149]. Consequently, carbonation curing can successfully decrease the water absorption and porosity of concrete produced [150].

3.4. Steam curing

Steam curing is used by researchers to enhance the overall productivity of concrete samples. Steam curing can reduce the production period for precast concrete samples to obtain the required strength, pre-stressing tension and lifting strength. Steam curing stimulates cement hydration, enhances early-strength concrete and accelerates the production of hydration products [151–156]; in

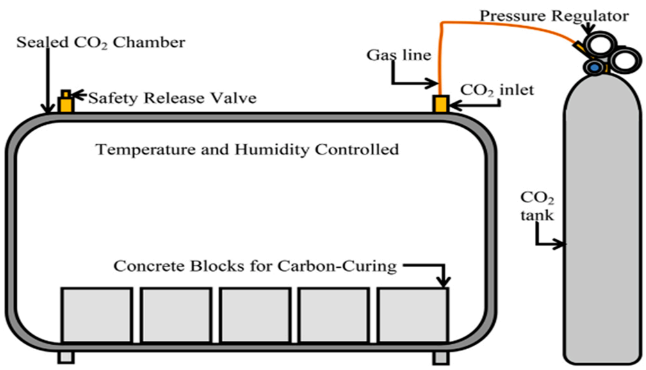

Fig. 5. Standard design for the compartment of carbon curing [127].

Table 3
Effect of duration and pressure of carbonation on compressive strength.

Ref.	w/b	Type of binder – binder ratio[a] %	Carbonation condition, pressure, duration	CO_2 uptake%	Compressive strength N/ mm^2
[130]	0.3	Wollastonite - 5 %, 15 %, 25 %	99%, 1.5 MPa, 2 h	18.34/26.53	49/30 at 7 day
[121]	0.4	Wollastonite - 5 %, 15 %, 25 %	99%, 1.5 MPa, 2 h	17.5/17.9/18.7	59/65/63 at 7 day
[131]	0.1	Ladle slag – 100 %	99.5%, 12.5 MPa, 1 day	9.35/13.22	39.5 at 35 day
[132]	0.15	KOBM steel slag - 0, 100 %	99%, 0.15 MPa, 2 h	9.35/13.22	109.3/94.3 at 28 day
[133]	0.5	MgO 0, 10 %, 20 %, 40 %	99.9%, 0.1 MPa, 7 day	-/37	–
[134]	0.45/ 0.35	Portlandite – 0, 42 %	12%, 0.1 MPa, 60 h	12.8	27/25 at 28 day
[135]	0.5	Cement kiln dust - 0, 5 %, 10 %, 20 %, 30 %, 40 %	99%, 0.069 MPa, 12 h	19.5/17.5	32/32/31/25/20/18at 28 day
[136]	0.4	MgO - 20 %, 40 %	99.8%, 0.55 MPa, 3 h	30/27/20/11.7	67/56 at 28 day
[137]	0.22–0.25	Iron particles - 58 %, 63 %, 69 %	99.9%, 0.1 MPa, 3 day	–	15/10/19 at 5 day
[138]	0.4	Volcanic ash - 0, 20 %, 30 %, 40 %, 50 %	5%, 0.1 MPa, 28 day	12.3/15.9/13.8/ 25.4/30.7	75/82/58/44/36 at28day
[139]	0.4	Red mud - 50 %	99%, 1.5 MPa, 4 h	18.5	4 after 120 min carbonation
[140]	0.3	Drinking water treatmentsludge – 10 %, 20 %, 30 %	10%, 0.1 MPa, 20 h	27.3/27.2/27.5/28.3	48/23/21/17 at 28 day

[a] binder ratio: the percentage of binder represents either a replacement ratio of cement or as an admixture(% of cement) to the concrete mix.

addition, it can adversely influence the late strength, durability and microstructure of concrete [155,157–159]. This adverse influence is mostly due to thermal damage resulting from steam curing [155,160]. This undesirable influence can be minimised by enhancing the control limitations in steam curing.

The limitations in steam curing are steam curing temperature, pre-curing time and required period [160,161]. Increasing the period of pre-curing might minimise the harmful influence of steam curing on concrete strength [162]. The rate of cement hydration reaction can be accelerated by increasing the temperature rate of steam curing, and the hydration heat accumulated in the early stage of cement is more important, thereby increasing the hydration degree [163,164]. The irregular distribution of calcium hydroxide CH crystals and hydrated calcium silicate C–S–H could be due to the rapid production of these crystals [165]. This phenomenon results in the roughening of the pore size of concrete, increasing the number of connected pores and a weakened structure of the occasioned hydration products [166], leading to the impermeability of concrete and decreased compressive strength [159,167]. The stability of ettringite can be reduced with high-temperature curing, thereby enhancing the production of calcium monosulpho aluminate [166].

Türkel et al. [168] stated that the compressive strength was decreased at 65 °C and 85 °C for 36 and 24 h of continuous curing, respectively. The rate of rapid early hydration and unequal distribution of hydration products led to a decrease in compressive strength value. The 28-day-compressive strength of concrete cured by steam with temperature rates of 50 °C and 60 °C increased initially and then decreased due to the rising steady temperature period [159]. By applying steam curing to the concrete samples, up to 80 % of the design strength for the short curing period can be obtained [152,159,169,170]; thus, the required tensile strength cannot be obtained [170,171].

Steam curing comprises four phases: pre-curing of concrete mix, heating, constant temperature and cooling [153,172]. The compressive strength of the industrial sand concrete under the steam curing phase and various steam curing temperature is presented in Fig. 6. The compressive strength of the industrial sand concrete increased quickly at an early age with the constant-temperature

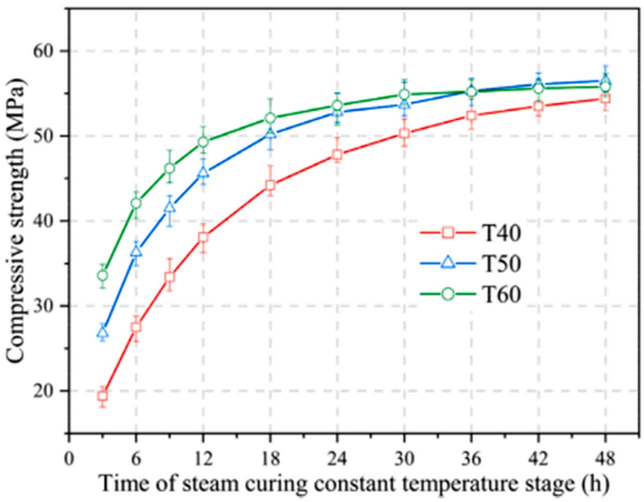

Fig. 6. Relationship between concrete age and compressive strength [172].

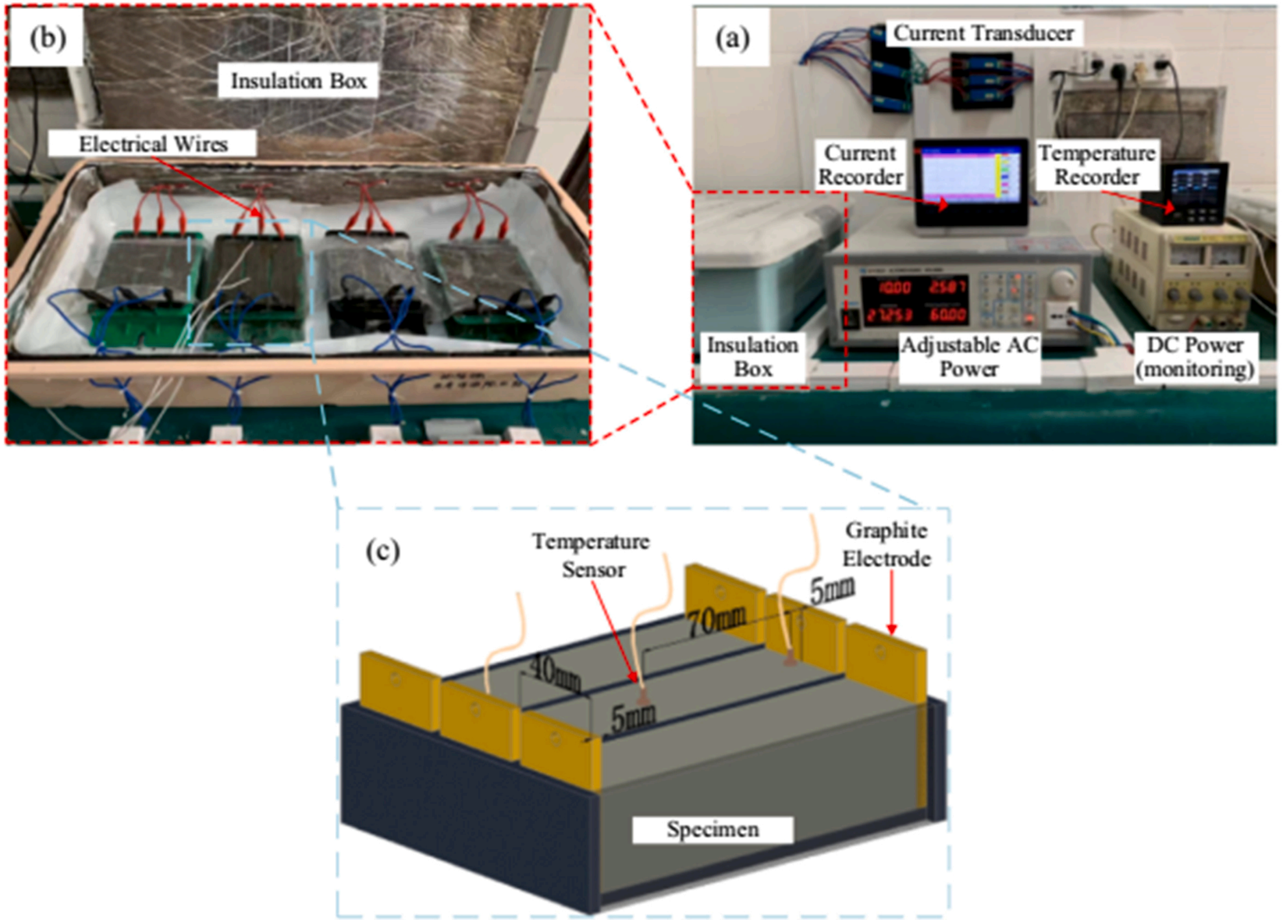

Fig. 7. Equipment used in electrical curing [184].

curing phase [172].

Saul [173] found a correlation between maturity and concrete strength by outlining the total temperature rates through a particular time as maturity. The steam curing of concrete samples is a complicated, connected environment of temperature and moisture [164,174]. Furthermore, the humidity, time and curing temperature affect concrete strength development [175,176]. Traditional maturing method does not consider variations in temperature rates in the different parts of the concrete samples during the hydration stage [173,177]. Most models of maturity strength were determined with 100% relative humidity and a water-cured environment [175,178]. The hydration method of concrete is an exothermic reaction; as such, the surface and environment of the concrete sample display significant differences [179,180].

3.5. Electric curing

Electric curing (EC) has been used in Russia since 1933 on a commercial scale in in-site casting and precast plants. Krylov [181] evaluated the EC method in his studies conducted at the Research Institute of Concrete and Reinforced Concrete. Electrical curing fundamentally affects the binder hydration and realising the performance expected from the concrete sample [182]. Heat curing is often implicated to increase the production rate by reducing the remoulding time to produce precast concrete. In some cases, the process of accelerated curing takes several days to achieve the strength required. Therefore, accelerating remoulding by electrical curing became an essential matter [183]. Yang et al. [184] adopted electrical curing to enhance the concrete properties. They conducted a series of experimental tests to determine the effects of alternating current frequency and voltages on the compressive strength of cement concrete by the equipment shown in Fig. 7. The frequency and voltage of alternating current electricity mainly affect the compressive strength of cement concrete, especially at an early age.

Bredenkamp [185] examined the influence of electric curing on cement concrete samples to determine the compressive strength development between 4 h and 28 days and optimise the curing methods. Constant intensities of electric curing between 300 and 500 V/m were studied. Electric curing was completed either after a certain exposure period or depending on obtaining whole energy of 76 kWh/m3. Despite obtaining about 50 % of compressive strength in only 240 min, the compressive strength of concrete samples exposed to EC was lower than that of concrete samples exposed to normal curing after 80 h. Wilson [186] conducted examinations by real-time adjustment and variable transformer of the input power. Heritage [187] carried out tests on temperature degree and control of electric curing at 60 °C and 80 °C; the treatment produced a linear increase of 40 °C/hour before heating. The compressive strength was not affected compared to normal curing, which decreased by 10% when exposed to 80 °C for 28 days of curing.

Electric techniques are unfamiliar substitutions which produce heat by Joule influence [188,189]. Direct or indirect techniques can be well-known. In indirect methods, embedded or surface electric resistors are organised to source heat; nevertheless, in the real arrangement of heating essentials, indirect electric curing is still represented by the surface-heating technique. In the direct technique, electrical curing is run through the concrete by entrenched electrodes [188].

3.6. Ambient and air curing

Ambient and air curing can be conducted in normal weather and without covering by any clothes or soaking by water. Muraleedharan and Nadir [190] stated that ambient curing was adequate for red mud geopolymers that require low-compressive strength, while higher strength and durability geopolymer specimens were suggested with increasing curing heat up to 80 °C. Marathe et al. [191] adopted air curing to determine the compressive strength of alkali-activated concrete containing recycled aggregates. The 28-day-compressive strength of concrete cured was 50 MPa. Hamad and Mohamad Ali [192] treated geopolymer concrete by air curing. They used the mixture of Na_2SiO_3 and NaOH as the alkaline solution and GGBFS as fine aggregate in different replacement levels. The results indicated that the compressive strength obtained was satisfied and adequate if compared with the control concrete.

Zhang et al. [193] used Portland cement and calcium sulfoaluminate cement (CSA) as binder materials to obtain concrete with high compressive strength at ambient curing. The 12-hour-compressive strength increased more than three times that of PC mortar strength (Fig. 8).

Xun et al. [194] studied the influence of water steam and air curing on the performance of RPC. The concrete produced with high-temperature steam curing had a denser microstructure and higher compressive strength than that produced by ambient curing; however, hot-air curing formed hydration products with crystallisation and surge porosity. The performance of RPC was influenced by temperature, pressure and air curing period, and critical times exist for various pressures and temperatures [195].

3.7. Water curing

Jinchuan et al. [196] assessed the influence of combining RPC replaced by 80 % GGBS on the 28-day compressive strength under water curing condition. The compressive strength decreased steadily when the replacement level of GGBS increased. However, all concrete mixtures had compressive strength higher than 100 MPa, excluding the concrete mixture containing an 80% replacement level of GGBS. Yazici et al. [67] examined the highest amount of GGBS in RPC for normal, autoclave and steam curing; the two groups of concrete were arranged with bauxite and granite aggregates. The compressive strength decreased under water curing and other curing conditions for a 20 % GGBS replacement level. The 28-day compressive strength values of concrete treated by normal curing water were 28.43, 26.45 and 29.16 MPa for three samples. The compressive strength values were 45.67, 46.76 and 45.34 MPa for the three samples.

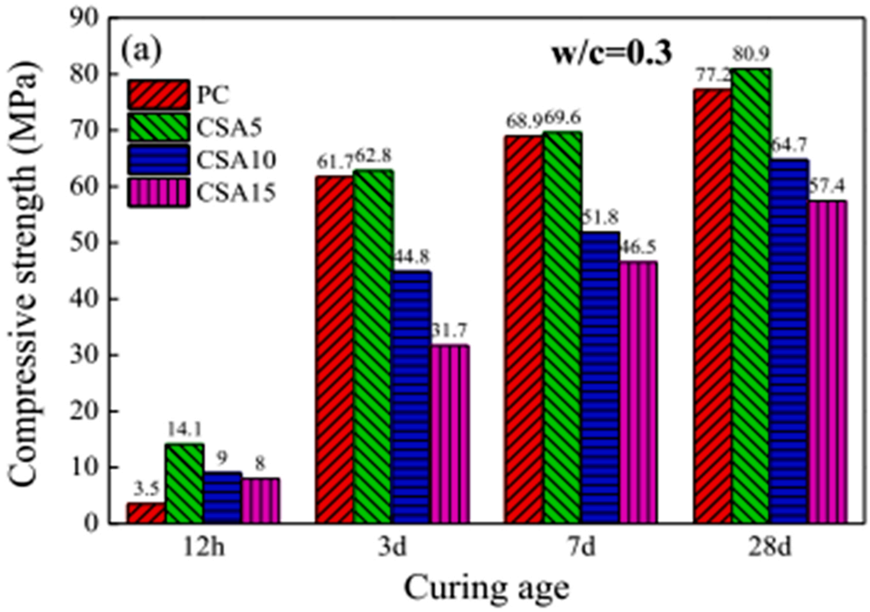

Fig. 8. Compressive strength of PC-CSA system with w/c of 0.3 [193].

4. Conclusion

This paper presents the influence of curing methods on the compressive strength of UHPC and concrete produced from different materials. Based on this review study, the following conclusions can be made:

1. The curing regime adopted in UHPC directly correlates with the water/binder ratio, cement type, aggregate type and content and concentration of admixtures. Curing regimes used for UHPC are categorised into thermal curing, water curing, ambient conditions, sealing, and microwave curing. Water and air curing can result in a higher porosity of the UHPC filled with free water. In contrast, steam and autoclave curing is the most favourable laboratory curing method that develops a relatively lower porosity than other curing regimes. Carbonation and electric curing develop high early strength in all UHPC systems but, if continued, can lead to a high drying shrinkage in UHPC.
2. Higher curing temperatures harm the strength of conventional concrete and UHPC at a later age; however, they have a beneficial effect at an early age. Autoclave curing is effective in providing an expansion to counteract the volume loss due to autogenous shrinkage.
3. Microwave curing can significantly improve the early strength of concrete. It can make the 12 h compressive strength of C30 concrete reach 10.3 MPa. The compressive strength of the UHPC matrix may reach around 105 MPa at 8 h. However, microwave curing decreased the long-term strength.
4. Steam curing condition is most commonly used to achieve high early age strength. However, it has adverse effects on the later age strength, which can be mitigated by incorporating supplementary cementitious material such as metakaolin and silica fume. Also, Steam curing can reduce the production period for precast concrete samples to obtain the required strength, pre-stressed tension and lifting strength, thereby increasing the early strength of concrete by accelerating the hydration. The most effective steam curing regime is in the temperature range from 50 °C to 80 °C and the curing period cycle of 24 h.
5. Carbonation curing is one of the new methods for treatment of concrete at early curing age and mainly results in reduced water absorption and porosity of concrete produced. Carbonation curing can contribute to compressive strength gain by 20–100 % at an early age and by 5–20 % after 28 day subsequent moisture curing for different mixtures. The early-age strength gain tends to be positively related to the carbonation degree because carbonation can densify the matrix, and C-S-H gel intermixed with calcium carbonates from carbonation can increase the resistance to mechanical loading.
6. Other concrete curing methods such as electrical, water, ambient and air curing are important to obtain high compressive strength. These curing methods could be used as a second stage after autoclave or steam curing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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University Malaysia Pahang, RDU213306.

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